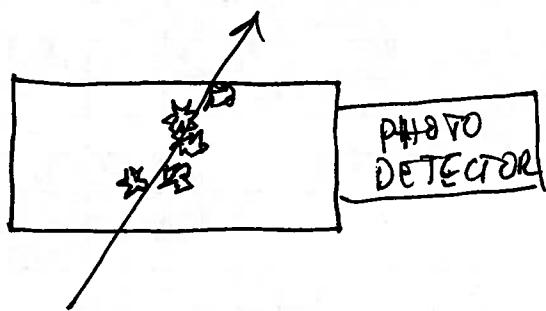


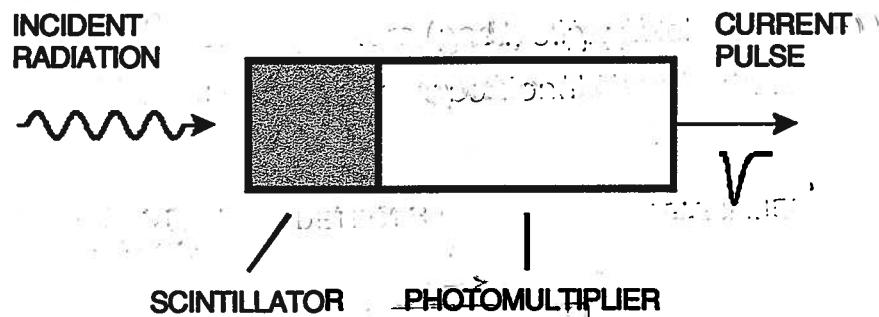
## Scintillation Detectors

- One of the oldest detection techniques  
(Recall ZnS screen from Rutherford's experiment and Röntgen's fluorescent screen)
- One of the most widely used particle detection device to this date
- Multi-purpose detectors
  - Trigger counter
  - Veto counter
  - Time of flight measurement
  - Tracking detectors
  - Calorimetry

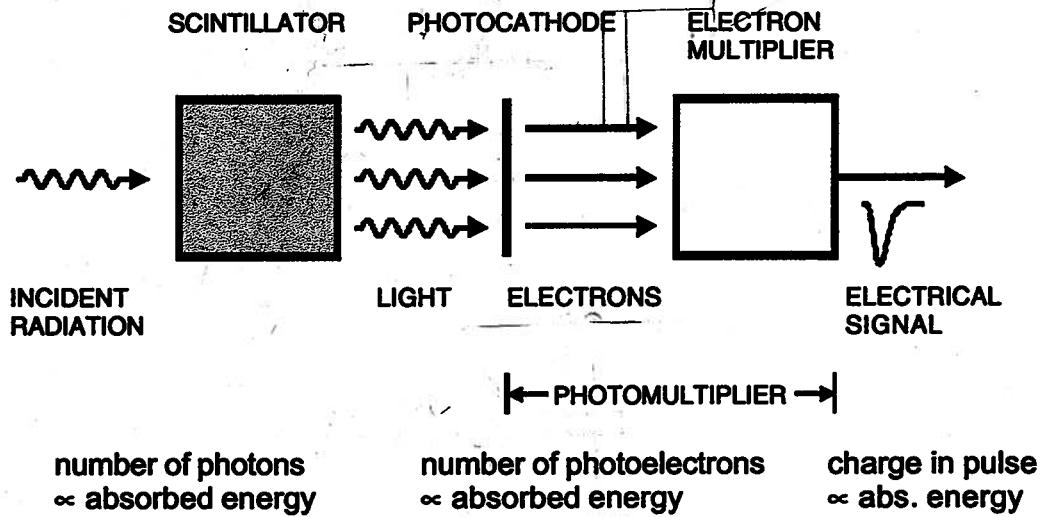


Energy deposition by high energy particle  
→ production of scintillation light  
→ photosensitive device + electronic read-out.

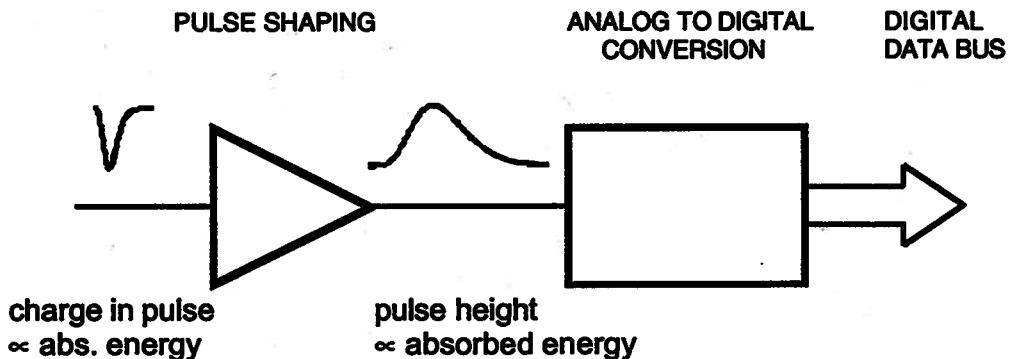
## Detector Functions



### Processes in Scintillator – Photomultiplier

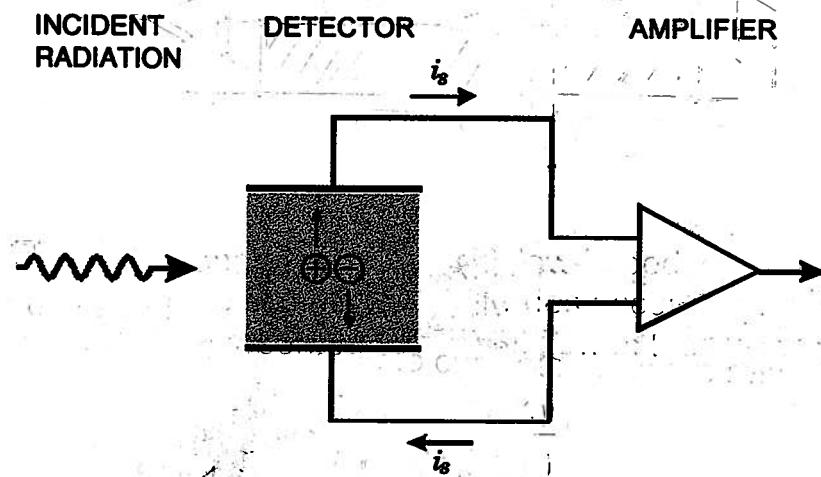


## Signal Processing

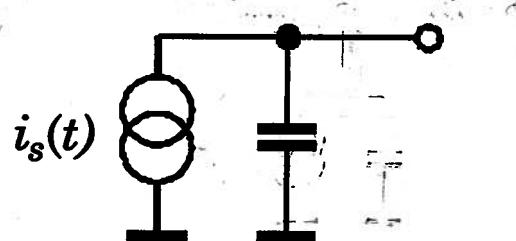


## 6. Ionization-Chamber

semiconductor detectors (pad, strip, pixel electrodes)  
 gas-filled ionization or proportional chambers, ...



**Model:**



## Scintillators

### Inorganic

→ high light output

~25 eV/ $\gamma$  in NaI(Tl)

→ slow decay time/response

~ $\mu$ s (CsI(Tl)) ; 0.62  $\mu$ s in BaF<sub>2</sub>

→ Inorganic crystals

### Organic

→ slow light output

~100 eV/ $\gamma$  required

→ fast decay time/response

~30ns in BaF<sub>2</sub>

→ Organic crystals

→ Organic liquids

→ Plastics

### + Gaseous Scintillators

Noble gases: Xe, Kr, Ar, He (also N<sub>2</sub>)

- Response extremely rapid (<1ns)

- Light emitted in UV (where PMTs are inefficient)

- Used in experiments with heavy charged particles or fission fragments.

### + Glasses

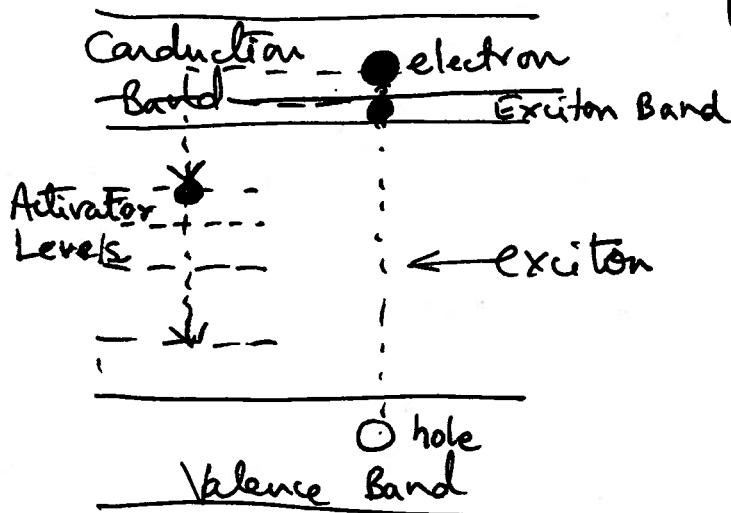
- Lithium or Boron silicates (Ceivium activated)

- low light output (< 25-30% of anthracene)

- Used in  $\beta^+$  detection, generally.

## Inorganic Scintillators

- The scintillation mechanism is an effect of the lattice. (Crystal structure of the material)
- Inorganic crystals, mainly alkali halides ( $\text{CsI}$ ,  $\text{NaI}$ ,  $\text{KI}$ , ..) with an activator impurity such as Tl



Most commonly used:

$\text{NaI(Tl)}$

non-alkali materials:

$\text{BGO}$  (Bismuth Germanate)  
 $\text{Bi}_4\text{Ge}_3\text{O}_{12}$

$\text{BaF}_2$ ,  $\text{ZnS(Ag)}$

- Incident particles can transfer energy by:
  - exciting an electron from the valence band to the conduction band  
→ creates a free electron & a free hole
  - exciting an electron from the valence band to the exciton band  
→ creates a bound e-h pair (exciton)

- free electrons, holes and the excitons can move freely through the lattice.
- Electrons combining with holes (or returning to the valence band) results in photon emission
  - frequency of the emitted radiation, response time depend on the band gap and the details of electron migration in the lattice.
- The dopants (or activator impurities) create additional activation centers (energy levels) in the forbidden gap.

These can be excited [by the excitons moving through the lattice], which then decay with photon emission.

The addition of the dopants thus increase the light yield, provide faster response and can also help match the radiation wavelength to the photocathode spectral sensitivity.

The decay time  $\propto e^{-E/kT}$

$E \equiv$  Energy of the excited impurity level.

- Sometimes the de-excitation can be radiationless (the impurity center becomes a trap.).

*Table 14. Properties of scintillating inorganic crystals*

Scintillator	Nal(Tl)	Lil(Eu)	CsI(Tl)	Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub>	BaF <sub>2</sub> <sup>a</sup>	CeF <sub>3</sub>	PbWO <sub>4</sub>
Density (g/cm <sup>3</sup> )	3.67	4.06	4.51	7.13	4.9	6.16	8.3
Melting point (°C)	650	450	620			1443	
Decay time (μs)	0.23	1.3	1.0	0.35	0.62	$6 \times 10^{-4}$	0.03
$\lambda_{\text{max}}$ (emission) (nm)	410	470	550	480	310	225	470
Light yield (photons/MeV)	$4 \times 10^4$	$1.4 \times 10^4$	$5.2 \times 10^4$	8200	6500	2000	1000
Radiation length $X_0$ (cm)	2.59	2.2	1.86	1.12	2.05		0.89
Critical energy (MeV)	12.5		10.2	8.8	12		13.6
Molière radius (cm)	4.3		3.8	2.7	3.4		8.5
Refractive index <i>n</i>	1.85		1.8	2.15	1.56		2.2
$(dE/dx)_{\text{min}}$ (MeV/cm)	4.13		5.1	8.07	5.72		1.68
Temperature coefficient of light output (%K <sup>-1</sup> )	-(0.22-0.9)	<0.2		-1.7	-0.6		2.16
Radiation damage	fair	fair	medium			small	
Hygroscopic	yes	weak	no			no	no

<sup>a</sup> BaF<sub>2</sub> has two scintillating components.

## Organic Scintillators

← Scintillation is a molecular process  
— Organic crystals (Anthracene  $C_{14}H_{10}$   
Naphthalene  $C_{10}H_8$ )

— Organic Liquids (Mixtures of one or more  
in a solvent  
e.g., p-Terphenyl ( $C_{18}H_{14}$ )  
in Toluene)

— Plastics (most popular & most widely used)  
polyvinyltoluene, polystyrene ← plastic solvents  
Typical solutes:  $C_{18}H_{14}$

∴ Organic scintillators are typically 2 or 3 active  
component mixtures in an organic base.

Primary fluorescence agent is excited by  
the energy loss of particles. The primary  
scintillation light from the deexcitation is  
emitted in the UV range. However, the  
fluorescence agent is opaque to its own light  
(short absorption length). So, a second fluoresce  
agent which absorbs the UV light and re-emits  
at longer wavelengths is added. (Wavelength  
Shifter). The emission spectrum of the 2<sup>nd</sup> agent  
is matched to the spectral sensitivity of the  
light receiver.

## Light Output

Average energy loss / photon for incident electrons

Scintillator  $E$  (eV/photon)

Anthracene 60

Nal 25

Plastic 100

BGO 300

- \* Light output lower for heavier particles at same  $E$
- \* efficiency of photo-detection is also important.  
For photomultipliers, efficiency  $\sim 30\%$ .

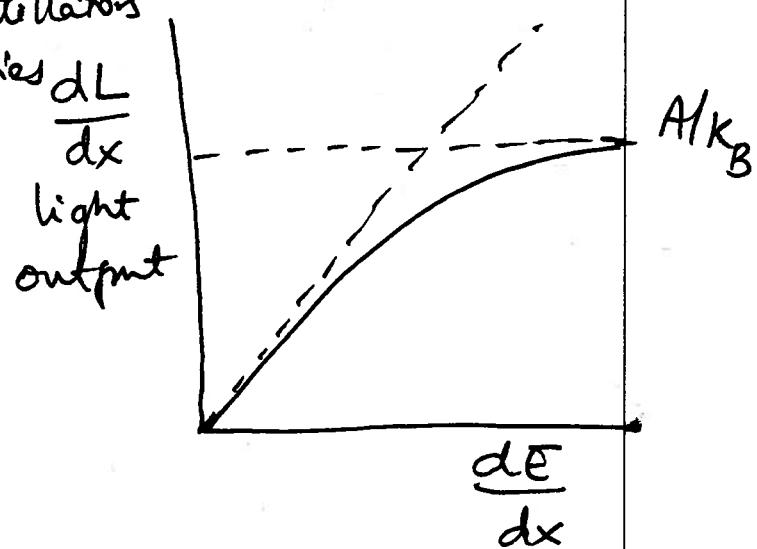
## Linearity of Response

Particularly, for plastic scintillators  
 $L \propto E$ , at high energies

Semi-empirical model

by Birks (1951)

$$\frac{dL}{dx} = \frac{A \cdot \frac{dE}{dx}}{1 + k_B \cdot \frac{dE}{dx}}$$



$A \equiv$  Absolute scintillation efficiency

$k_B$  = Birks density parameter

→ Higher the ionization density, higher the quenching interactions, lower the light.

For small  $\frac{dE}{dx}$ ,  $\frac{dL}{dx} \approx A \cdot \frac{dE}{dx}$ ; Large  $\frac{dE}{dx}$ ,  $\frac{dL}{dx} \approx \frac{A}{k_B}$  ②

We already talked about scintillators used as calorimeters

Some examples:

Pure CsI —  $\xleftarrow{\text{KTeV}}$  has a fast component, 6 ns  
so, desirable in high-rate experiments

CsI(Tl) — Babar

When Tl is added, response is much slower,  
but, light yield increases significantly  
(needed to detect low energy signals).

PbWO<sub>4</sub> — dense, fast, radiation hard  
Used in CMS

Mainly used as EM calorimeters

High Z is good for shower production

Bremsstrahlung for electrons ( $\sigma \propto Z^2$ )

photoelectric effect ( $\sigma \propto Z^5$ )

and pair production ( $\sigma \propto Z^2$ ) for photons

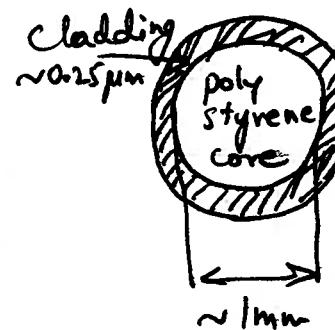
Scintillation Sampling Calorimeters:

Use organic plastic scintillators in the form of fibres or plates

ZEUS, CDF

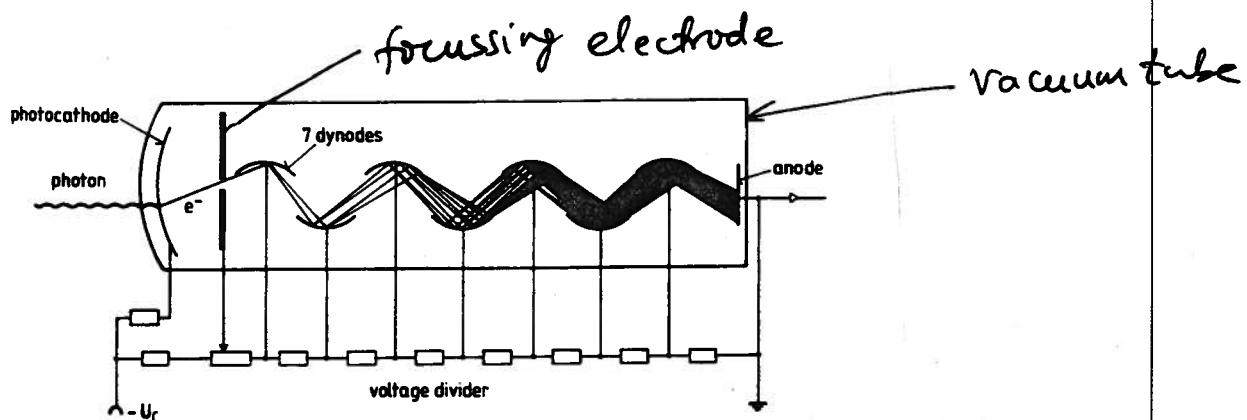
## Light Transfer to Photodetectors :

- Light Guides:  
transfer by total internal reflection
- Wavelength Shifter (WLS) bars  
Absorb and re-emit at longer wavelengths  
to match photodetector sensitivity.
- Fibers:
  - clear fibers (Total internal reflection)
  - WLS fibers
  - Scintillating fibers  
(used in tracking)



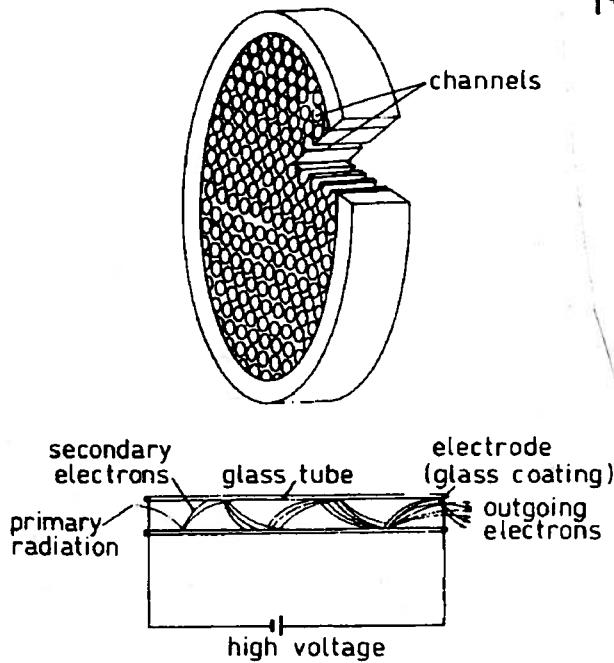
## Photo Detectors

- PhotoMultiplier Tube (PMT)



- Photons from the scintillator impinge on the photocathode, electrons are emitted via photoelectric effect. [photocathode coated with a low-work function material]
- The emitted photoelectrons are accelerated and focused onto the first dynode of the tube. For every electron incident more secondary electrons are produced at the dynode (BeO, Mg-O-C<sub>60</sub>)
- The amplified current is collected at the anode.
- PMs are sensitive to B fields, even earth field (30-60 μT). Mu-metal shielding used.

## Micro Channel Photomultipliers (Plates)



Microchannel Plates contain a large number of small tubes / channels  
(dia 10-50  $\mu\text{m}$ ,  
length 5-10 mm)

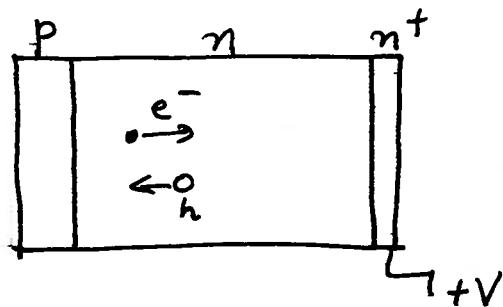
- Glass tubes coated inside with a resistive layer (or holes in lead-glass plate)  
 $\sim 1000$  V applied across

- Each channel acts as a continuous dynode (see figure). Amplifications  $\sim 10^5 - 10^6$  possible
- Multi-step micro-channel PMTs are possible
- Bent single-channel electron multipliers for space applications
- fast signal; low path-length fluctuations, hence, smaller transit-time spread  
 $\approx 50$  ps as opposed to 200 ps for conventional PMT
- less sensitive to B-field

## Photo Diodes

- High Q.E.

$\sim 80\% @ \lambda \sim 700 \text{ nm}$   
gain  $G = 1$



## Avalanche Photo Diodes (APD)

Add a high voltage (high electric field) region to effect avalanche multiplication.

High reverse bias

Voltage  $\sim 100-200 \text{ V}$

$G \sim 100$

## Photo Triodes (vacuum tube Triode)

Single stage PMT

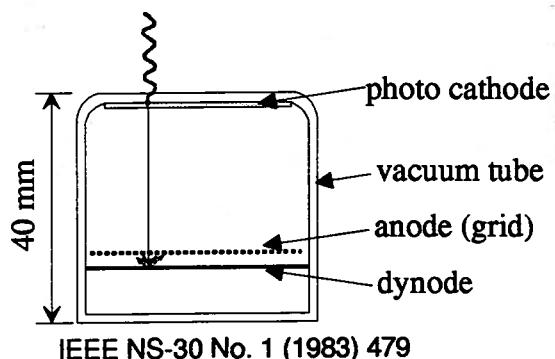
not Silicon!

$G \sim 10$

works in axial B-fields

of 1 T

Read-out of lead-glass  
end-cap calorimeter in OPAL, DELPHI



IEEE NS-30 No. 1 (1983) 479

## Visible Light Photon Counter (VLPC)

A variant of the solid-state photomultiplier  
Si:As Impurity Band Conduction Avalanche Diode

Hole drifts towards

highly doped region

and ionizes a donor atom  $\gamma$

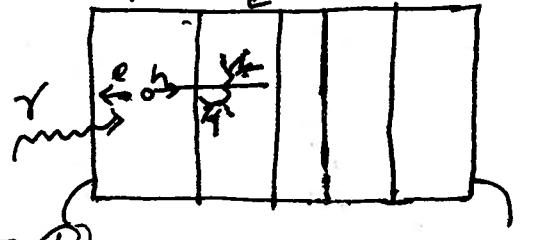
$\rightarrow$  free electron

multiplication by ionization  $\oplus$   
of more neutral donor atoms

Q. E.  $\sim 70\%$  ;  $G \sim 20,000$

Rate capability  $\sim 10$  MHz.

Intrinsic Region      Gain region

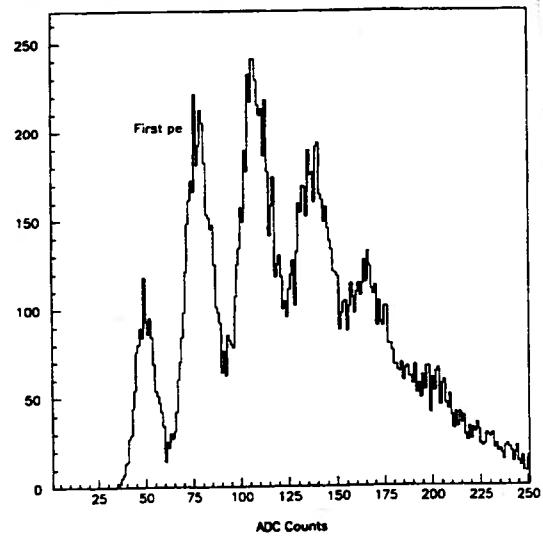


(DΦ VLPC  
for the fiber tracker)

Bias voltage  $\sim 7V$

Operating Temperature

$\sim 7-14$  K



## Scintillating Fiber Tracker

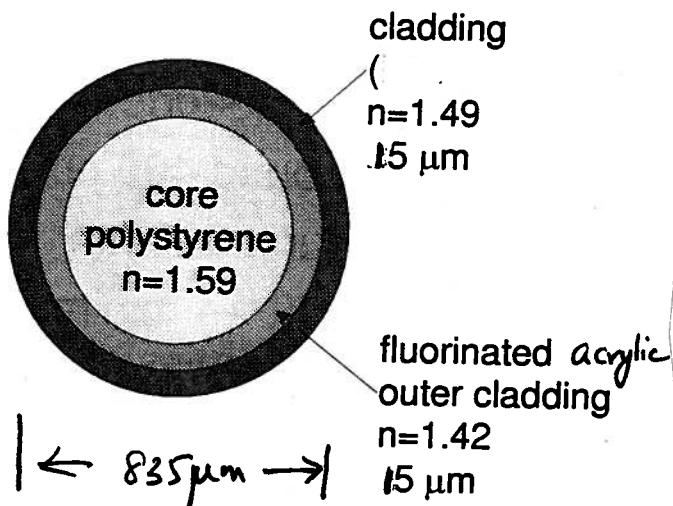
- Plastic fibers
- Capillary fibers filled with liquid scintillator

### Advantages

- High geometrical flexibility
- fine granularity
- low mass
- fast response ( $\sim$  ns)  
→ first level trigger

## DΦ fiber Tracker

Multi-clad fibers



The addition of second cladding increases light trapping by 70%.

Also improves robustness of the fibers.

Core polystyrene doped with 1% p-terphenyl (PTP) and 1500 ppm 3-hydroxyflavone (3HF)

peak emission  $\lambda \sim 530 \text{ nm}$

The scintillating fibers are mated to 11 m long multi-clad fiber wave guides which conduct light to VLPcs on the platform (16)

## Cerenkov Detectors

Detectable cerenkov light is produced when a particle traverses a medium with a speed  $v > c/n$   $\leftarrow$  threshold effect

$c/n$  = velocity of light in the medium  
 $n$  = refractive index of the medium.

Dielectric materials with  $n \gg 1$  are good candidates for Cerenkov detectors.

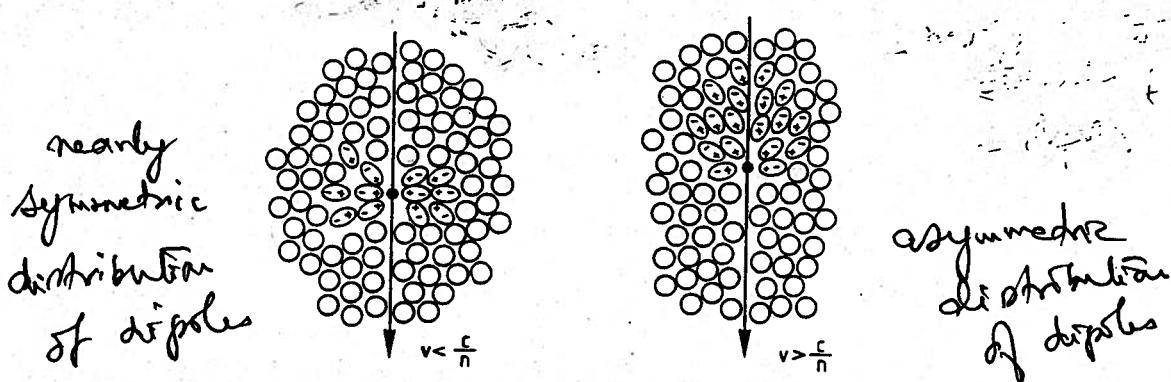
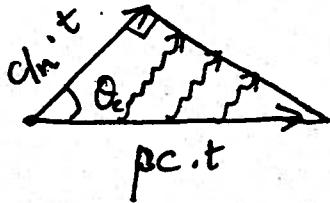


Fig. 6.7. Illustration of the Cherenkov effect [68].

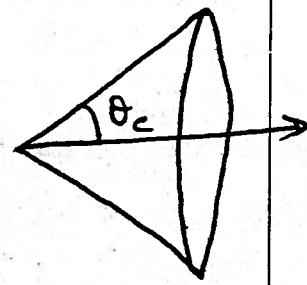
Charged particle polarizes atoms along its path  
→ electric dipoles

If  $v < c/n$ , the dipoles are symmetrically situated along particle's path  
⇒ integrated dipole field vanishes  $\Rightarrow$  no radiation

If  $v > c/n$ , symmetry is broken  
⇒ non-vanishing dipole field  $\Rightarrow$  Cerenkov radiation



$$\cos \theta_c = \frac{1}{n\beta}$$



In time  $t$ , particle travels a distance  $= \beta c t$

light travels a distance  $= \frac{c}{n} \cdot t$

$$\therefore \cos \theta_c = \frac{1}{n\beta}$$

In principle, the emission of a Cerenkov photon leads to a recoil of the charged particle, which changes its direction slightly.

Taking this into account gives,

$$\cos \theta_c = \frac{1}{n\beta} + \frac{\hbar k}{2p} \left( 1 - \frac{1}{n^2} \right)$$

$\hbar k$  = momentum of the photon  
of the photon

$\hbar k$  = momentum of the photon ;  $k = 2\pi/\lambda$

but,  $\hbar k \ll p$  ;  $\therefore$  2nd term can be neglected.

Emission of Cerenkov radiation is a threshold effect  
Cerenkov radiation is emitted only if  $v > c/n$

or  $\beta > \frac{1}{n}$  i.e.,  $\beta_{th} \approx \frac{1}{n} \Rightarrow \theta_c \approx 0$  (forward)

$\theta_c$  increases and reaches a maximum for  $\beta = 1$

$$\theta_{max} = \cos^{-1} \frac{1}{n} \quad \text{'Saturated' angle}$$

The threshold velocity for the emission of Čerenkov radiation corresponds to a threshold energy,

$$E_{th} = \gamma_{th} \cdot m_0 c^2$$

$$\text{where } \gamma_{th} = \frac{1}{\sqrt{1 - \beta_{th}^2}} = \frac{1}{\sqrt{1 - \frac{1}{n^2}}} = \frac{n}{\sqrt{n^2 - 1}}$$

Čerenkov detectors have one or more of the following properties

- The existence of a threshold for radiation
- The Čerenkov half-angle  $\theta_c$  depends on  $\beta$  of the particle
- Number of emitted photons depends on the  $\beta$  of the particle

$$\frac{d^2N}{d\Omega d\omega} = \frac{\alpha^2 z^2}{\pi c} \sin^2 \theta_c = \frac{\alpha^2 z^2}{n e m c^2} \left(1 - \frac{1}{\beta^2 n^2 c E}\right) \approx 370 \sin^2 \theta_c(E) / \text{eV/cm}$$

Number of photoelectrons detected in a device,

$$N_{p.e.} = L \cdot \frac{\alpha^2 z^2}{n e m c^2} \int \epsilon_{coll}(E) \epsilon_q(E) \sin^2 \theta_c(E) dE$$

$\uparrow$                            $\uparrow$   
 photon collection efficiency      Quantum efficiency (PMT)

$\simeq L \cdot N_0 \langle \sin^2 \theta_c \rangle$   
 Typical  $N_{p.e.} \sim 15-20 / \text{cm}^{-2}$

medium	n	$\theta_{\max} (\beta=1)$	$N_{ph} (\text{eV}^{-1} \text{cm}^{-1})$
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

- Contribution of Cerenkov radiation to energy loss is small compared to that of ionization and excitation  
 $\hookrightarrow$  < 1% of ionization loss for MIPs  
 $\hookrightarrow$  in gases with  $Z \geq 7$
- Light yield is small compared to scintillation  
 $\hookrightarrow$   $10^3 - 10^4$  times smaller  
in a Cerenkov calorimeter  
 $\hookrightarrow$  Only tracks in the shower with  $v > c/n$  produce a detectable signal